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The Trade-Offs/Synergies and Their Spatial-Temporal Characteristics between Ecosystem Services and Human Well-Being Linked to Land-Use Change in the Capital Region of China

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Abstract: With the rise of the strategy of Coordinated Development for the Beijing-Tianjin-Hebei Region, it is necessary to evaluate the trade-offs/synergies of the survival environment and human well-being in Hebei, the capital region of China. However, existing methods cannot analyze and express trade-offs/synergies of two or more variables simultaneously. Therefore, this paper proposes a new framework to express the trade-offs/synergies among land-use intensity, ecosystem services, and human well-being. In this paper, we first identified the land-use intensity change and land-use transformation and evaluated ecosystem services and human well-being in Hebei from 2000–2015 under the Millennium Ecosystem Assessment framework. Then, the trade-offs/synergies of the three indicators were determined by GIS-based methods and MATLAB. The results show that land-use intensity and human well-being mainly present a synergistic relationship, while ecosystem services and land-use intensity mainly present a trade-off relationship, and ecosystem services and human well-being also present a trade-off relationship in Hebei during 2000–2015. In addition, some regional solutions to achieve sustainable development were proposed: region 1 needs to adjust land-use structure, region 2 needs to protect the ecological environment to improve the supply of ecosystem services, and region 3 needs to commit to improving the regional comprehensive human well-being. This study not only proposes a new framework for analyzing trade-offs/synergies of land use intensity, ecosystem services, and human well-being, but it also provides regional solutions for Hebei to achieve sustainable development.

Keywords: trade-offs/synergies; land-use change; ecosystem services; human well-being; sustainable development

1. Introduction

Global environmental changes have put great pressures on ecosystems [1]. On the one hand, humans seek space for development to improve human well-being [2]; on the other hand, humans need to protect our common home for sustainable development [3]. To achieve win-win outcomes, it is essential to conduct a trade-off/synergy analysis on the survival environment and human well-being [4]. Ecosystem services (ESs) [5] are the benefits that humans obtain from ecosystems, and they can be divided into provisioning services, regulating services, supporting services, and cultural services from the Millennium Ecosystem Assessment (MA) [6]. It builds a bridge between ecosystems and socioeconomic systems and has real potential for planning and decision making. Human well-being (HWB) [7] is the activity or condition that people think is valuable. From the perspective of the MA framework, HWB contains health, safety, good relationships, basic material needs of maintaining a high-quality life, and the freedom of choice and action [8]. Land-use change alters the ES value, and ESs are the foundation of HWB [9]. MA shows that increasingly extensive and intensive human activities lead to continuous declination in ES, which further influences HWB and threatens regional and even global ecological security. Moreover, the Sustainable Development Goals of the United Nations aim to completely solve global social, economic, and environmental development problems in an integrated manner from 2015 to 2030 and turn to the path of sustainable development [10]. In addition, distinguishing the different factors that disturb ecosystems and how ecosystems contribute to society and the economy are important to sustainable development. Therefore, integrated research on land-use change, ES, and HWB is crucial.

Different ESs interact with each other, and they often show two kinds of relationships under internal and external influences: trade-off and synergy [11]. Trade-off was first adopted in the physics field to describe the relationships between signals. Then, it was applied in the economy field [12,13]. The field of ecology uses it to indicate a situation in which an increase in one ES causes a decrease in another ES, which is also known as a competitive relationship. Synergy is a situation where two or more ESs increase or decrease at the same time [14]. Trade-offs can be divided into three categories: spatial trade-offs [15], temporal trade-offs [16], and reversible trade-offs [17]. Spatial trade-offs usually indicate the spatial relationship among different ESs caused by the spatial difference in the supply and demand capabilities of ESs [18,19]. Temporal trade-offs describe the relationship between current conditions and future conditions [20]. Reversible trade-offs refer to the ability of ESs to recover to their original state after the current disturbance, which is related to the resilience of natural processes [21].

Many studies identify trade-offs/synergy of ES at the watershed, national, and regional scales. Previous studies mostly concentrate on trade-offs/synergies in spatial-temporal scale characteristics [22,23], driving mechanisms and impact distributions [24], and scenario analysis [25]. There are a variety of tools and approaches to quantitatively analyze trade-offs/synergies of ES from existing studies, which can divided into four categories [26]. The first is the trade-off analysis based on statistical methods, such as correlation analysis, to analyze the statistical characteristics of changes in the ESs [27]. The second is the trade-off analysis based on spatial analyses method, including GIS. The research has constructed an assessment framework at the country scale to measure trade-offs, synergies, and losses among multiple ESs and revealed their spatial heterogeneity and gradient effects [28]. The third is trade-off analysis based on scenario simulation. The study explored the trade-offs/synergies of ecosystem service value of Anyang city during 1995–2025 under different policy scenarios [29]. The last is the trade-off analysis based on ecosystem service flow [30]. However, this method is usually used in studies of ES trade-off analysis where supply and demand are easier to quantify, such as freshwater supply service and fishery production service [31]. In general, the four methods are usually used in combinations in practical application. Furthermore, trade-offs and synergies not only exist among ESs but also exist among the driving forces of ESs [32] and among the beneficiaries of ESs [20,33]. In addition, trade-offs/synergies not only exist among variables of the same type but also exist among variables of different types [34]. For example, the literature [35] researched the trade-offs between biological conservation and ESs, and the study analyzed the trade-offs between ESs and HWB [36].

However, most previous studies mapped and analyzed trade-offs/synergies between two types of variables, such as the trade-offs between biodiversity and economic development, the trade-offs between ESs and HWB, and the trade-offs between ecological protection and HWB. This is because that current research methods have difficulties in analyzing and expressing the trade-off/synergies among more than two types of variables. Therefore, the knowledge about spatiotemporal heterogeneity and regional differences of trade-offs/synergies among more than two types of variables is also lacking, especially the trade-offs/synergies among the driving factors of ecosystems, ESs, and HWB in a certain region. To fill this scientific gap, this paper proposes a research framework of express trade-offs/synergies among three types of variables to explore the relationships among the driving factors of ecosystems, ESs, and HWB using GIS-based methods and MATLAB. This framework can assist researchers, managers, and policy makers to identify spatiotemporal trade-off/synergies among the driving factors of ecosystems, ESs, and HWB and help sustainable land-use management and policy decision making.

With the launch of the strategy of Coordinated Development for the Beijing-Tianjin-Hebei Region (BTH Coordinated Development), Hebei Province is the ecological support area of the Beijing-Tianjin-Hebei Region. Changes occur in Hebei Province, such as the rapid development of economy and the expansion of urbanization, leading to changes in the survival environment and HWB in Hebei. To explore effective pathways of eco-civilization construction and promote the coordination of population, economy, resources, and environment, it is essential to study the trade-offs/synergies of the survival environment and HWB and provide a scientific basis for formulating sustainable and suitable protection policies for local conditions. This paper adopts spatial analysis and logical analysis to study trade-offs/synergies of land-use intensity (LUI), ESs, and HWB in Hebei based on socioeconomic data and geographic data from 2000–2015. The main purposes of this paper are (1) to identify LUI change and land-use transformations in Hebei from 2000–2015; (2) to model and quantify the spatiotemporal changes of ESs and HWB; and (3) to analyze the trade-offs/synergies of LUI, ESs, and HWB in Hebei. This study not only proposes an analytical framework for simultaneously exploring the trade-offs/synergies among three or more variables of different types but also provides a scientific basis for achieving a win-win situation between the improvement of ESs and the improvement of HWB, which is beneficial to the promotion of regional sustainable development.

2. Study Area and Data

2.1. Study Area

The terrain of Hebei Province is high in the northwest and low in the southeast, sloping from northwest to southeast. The landforms are complex and diverse, with many types of plateaus, mountains, hills, basins, and plains. Hebei has a temperate continental monsoon climate. The annual sunshine hours are 2303.1 h, and the annual frost-free period is 81–204 days; the average annual precipitation is 484.5 mm, and the precipitation distribution is characterized by more precipitation in the southeast and less precipitation in the northwest; the average temperature in January is below 3 °C, and the average temperature in July is 18 °C to 27 °C. The four seasons are distinct. Hebei Province is the only place through which the capital Beijing connects all parts of the country. With the introduction of the BTH Coordinated Development strategy, Hebei has undertaken the transfer of industries from Beijing and Tianjin. The population has increased rapidly, the level of industrialization and urbanization has increased rapidly, the degree of intensification of agricultural land has intensified, and grain production continues to increase. Hebei has experienced serious ecological and environmental problems, such as soil erosion in the Taihang Mountains and Yanshan Mountains, intensified desertification on the Bashang Plateau, degradation of coastal and estuary ecosystems, and land subsidence. The geographical location and administrative division of Hebei province is shown in Figure 1.

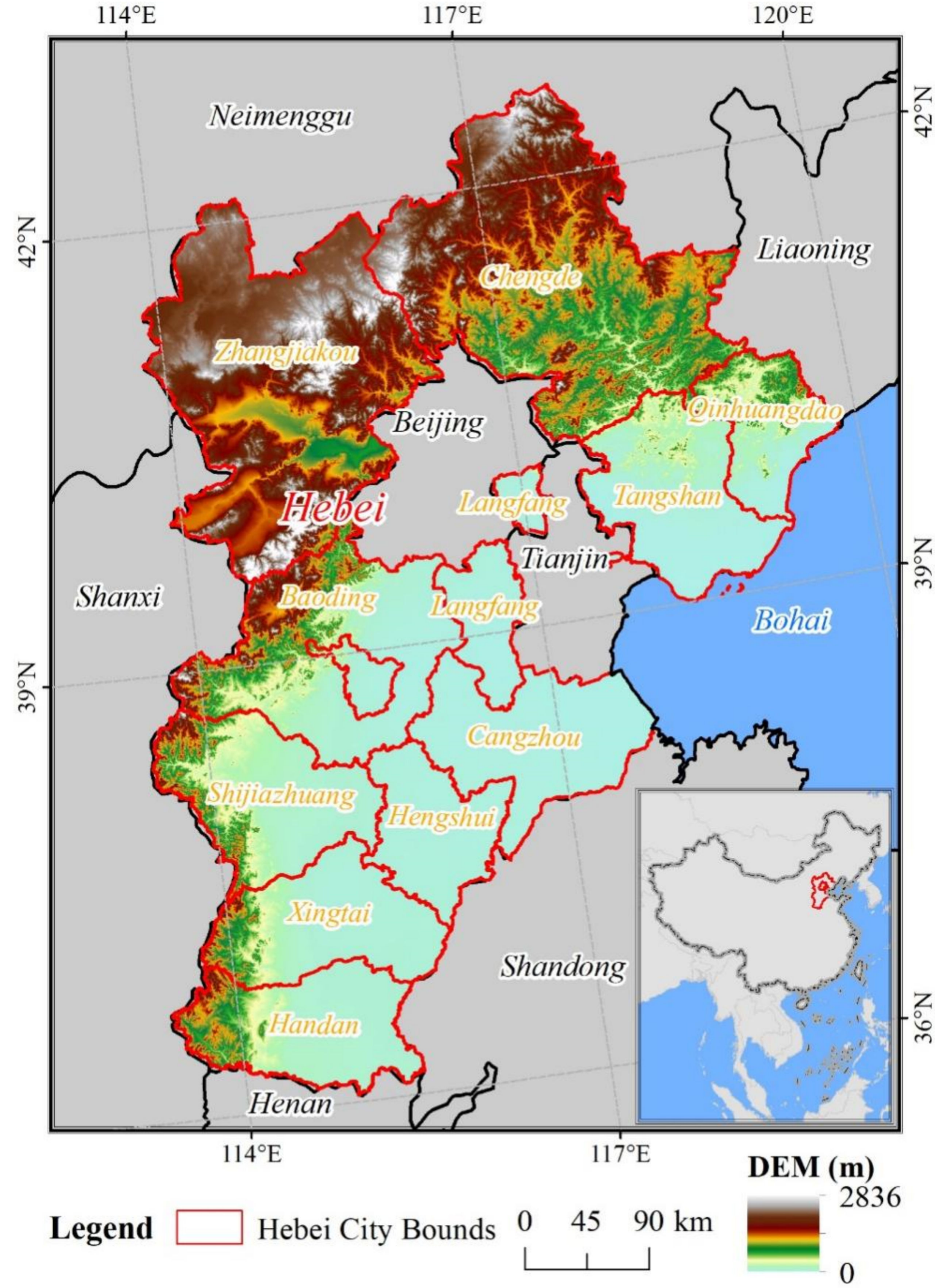

Figure 1. The geographical location and administrative division of Hebei province.

2.2. Data

The data used in ES assessment include meteorological data, such as precipitation, temperature, and solar radiation; soil data, such as soil type, physical and chemical properties, water content, and depth; and remote sensing data, such as NDVI and evapotranspiration, which are shown in Table 1. Precipitation, temperature, and solar radiation come from meteorological stations, and kriging interpolation is executed to obtain data at 1000 m resolution. Moreover, all data, including statistic data, are resampled to 1000 m to maintain data consistency. In addition, due to access to research data, the most recent data available for this study is from 2015.

Table 1. Data and their source.

Type	Resolution	Source	Websites
Meteorological data	1000 m × 1000 m	National Meteorological Science Data Center	http://cdc.nmic.cn (accessed on 14 April 2022)
DEM	1000 m × 1000 m	International Scientific Data Service Platform	http://datamirror.csdb.cn (accessed on 14 April 2022)
Land-use data	1000 m × 1000 m	Institute of Geographic Sciences and Natural Resources Research	http://www.resdc.cn/ (accessed on 14 April 2022)
Evapotranspiration data	1000 m × 1000 m	MOD16A3	http://www.geodata.cn (accessed on 14 April 2022)
Soil data	1000 m × 1000 m	Harmonized World Soil Database version 1.1	http://www.fao.org (accessed on 14 April 2022)
NDVI	1000 m × 1000 m	Institute of Geographic Sciences and Natural Resources Research	http://www.resdc.cn/ (accessed on 14 April 2022)
Statistic data		Hebei Statistical Yearbook	http://tjj.hebei.gov.cn/ (accessed on 14 April 2022)
Boundary data		National Earth System Science Data Center	http://www.resdc.cn/ (accessed on 14 April 2022)

3. Methods

3.1. Land Use Transfer Matrix

This study adopts a land-use transfer matrix to analyze the transfer direction and transfer quantity of different land-use types [37]. The formula of the land-use transfer matrix is as follows:

$$S_{ij} = \begin{bmatrix} S_{11} & \cdots & S_{1n} \\ \vdots & \ddots & \vdots \\ S_{n1} & \cdots & S_{nn} \end{bmatrix} \tag{1}$$

where S represents the study area; n represents the land-use type; i, j ($i, j = 1, 2, 3, \cdots, n$) represent the land-use type before and after transformation; and S_{ij} represents the study area of land-use type i converted to land-use type j.

3.2. Land-Use Intensity

Humans change land-use structure and pattern, and human preferences and needs lead to different investments and uses of different land resources. The most direct manifestation is the change in LUI [37]. This manifestation not only influences ecosystem structure and function in regions but is also the important driving force to stimulating changes in ecosystem functions. This paper uses spatiotemporal changes of LUI to characterize the influence of human activities. The formula is as follows [38]:

$$\mathrm{LUI} = \sum_{i=1}^{n} A_i \times \frac{S_i}{S} \tag{2}$$

where LUI represents the value of land use intensity of a region; A_i represents the land use intensity coefficient of land-use type i, which indicates the human activity intensity per unit land area. The larger the value is, the stronger the impact of human activities is. The land-use intensity coefficient of different land-use types is shown in Table 2; S_i is the area of land-use type i in a county, and S is the total land area of a region.

Table 2. The land-use intensity coefficient of different land use types [38].

Land-Use Type	Farmland	Forest	Grassland	Water Body	Urban Land	Bare Land
Land-use intensity coefficient	3	2	2.5	2	4	1

3.3. ES Assessment

(1) Water yield

This paper adopts "water yield" module in Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) [39] to evaluate the water yield in the study area. This module is based on the theory of water balance. The unit water yield of each grid is the precipitation of the grid minus the evapotranspiration. The formula is as follows [40]:

$$Y_{xj} = \left(1 - \frac{AET(x)}{P_x}\right) \times P_x \quad (3)$$

$$\frac{AET(x)}{P(x)} = 1 + \frac{PET(x)}{P(x)} - \left[1 + \left(\frac{PET(x)}{P(x)}\right)^{\omega}\right]^{\frac{1}{\omega}} \quad (4)$$

where Y_{xj} is the annual water yield of land-use type *j* in grid *x*; *AET(x)* is the actual evapotranspiration of land-use type *j* in grid *x*; P_x represents the annual precipitation of grid *x*; *PET(x)* represents the potential evapotranspiration of grid *x*; and ω(x) represents the nonphysical parameter, and the calculation for ω(x) is as follows [41]:

$$\omega(\mathrm{x}) = \mathrm{Z}\frac{AWC(x)}{P(x)} + 1.25 \quad (5)$$

where *AWC(x)* refers available soil moisture in grid *x*; Z represents empirical constant, which can indicate regional precipitation distribution and other hydrogeological features.

(2) Soil conservation

Ecosystems play an important role in preventing soil erosion and maintaining the function of soil filtering pollutants. This paper uses Revised Universal Soil Erosion Equation (RUSLE) to assess soil conservation service in the study area. The formula of RUSLE is as follows [42]:

$$\mathrm{A} = \mathrm{f} \times \mathrm{R} \times \mathrm{K} \times \mathrm{LS} \times \mathrm{C} \times \mathrm{P} \quad (6)$$

where A is the amount of soil erosion per unit area; f is a constant from the U.S. system to the international system, which is 224.2; R is the rainfall erosivity factor, and the formula is as follows:

$$\mathrm{R} = \sum_{i=1}^{12} 1.7535 \times 10^{\left(1.5log_{10}\frac{P_i^2}{P} - 0.08188\right)} \quad (7)$$

where P_i is the monthly average precipitation (mm), and *p* is the annual average precipitation. K is the soil erodibility factor, and the erosion-productivity impact calculator (EPIC) model [43] was selected to estimate the value of K as follows:

$$\mathrm{K} = \left\{0.2 + 0.3\exp\left[-0.0256S_a\left(1 - \frac{S_i}{100}\right)\right]\right\} \times \left(\frac{S_i}{C_i + S_i}\right)^{0.3}\left[1 - \frac{0.25C}{C + \exp(3.72 - 2.95C)}\right] \times \left[1 - \frac{0.7S_n}{S_n + \exp(-5.51 + 22.9S_a)}\right] \quad (8)$$

$$S_n = 1 - \frac{S_a}{100} \quad (9)$$

where S_a, S_i, C_i, and *C* refer to grain content, sand content, clay content, and organic carbon content, respectively. *LS* refers to soil loss generated by a slope of a certain slope. *LS* is calculated by the DEM, and its calculation formula is as follows [44]:

$$\mathrm{L} = \left(\frac{\lambda}{22.13}\right)^{m}\begin{cases} m = 0.2, & \theta < 1^\circ \\ m = 0.3, & 1^\circ < \theta < 3^\circ \\ m = 0.4, & 3^\circ < \theta < 5^\circ \\ m = 0.5, & \theta > 5^\circ \end{cases} \quad (10)$$

$$S = \begin{cases} 10.8 \sin\theta + 0.03, \theta < 5^\circ \\ 16.8 \sin\theta - 0.5, 5^\circ \le \theta \le 10^\circ \\ 21.9 \sin\theta - 0.96, \ \theta > 10^\circ \end{cases} \quad (11)$$

where λ is the slope, and m is a dimensionless constant depending on the slope θ.

C is the vegetation coverage and management factor and refers to a certain area of soil loss under certain coverage and management levels. Its calculation formula is as follows according to [45]:

$$C = \begin{cases} 1, f_c = 0 \\ 0.6508 - 0.3436 lg f_c, 0 < f_c < 78.3\% \\ 0, f_c \ge 78.3\% \end{cases} \quad (12)$$

$$f_c = \frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}} \quad (13)$$

where P is the soil and water conservation factor and refers to the ratio of soil loss under water and soil conservation measures to soil loss cultivation without these measures on that slope. It is calculated as follows [46]:

$$P = 0.2 + 0.03S \quad (14)$$

where S is the slope.

(3) Carbon sequestration

Ecosystems not only store carbon in trees, biomass, and soil but also fixes carbon dioxide in plants and soil, thereby holding additional carbon every year. Carbon storage is an important indicator in terrestrial ecosystems; it is different in different land-cover types, and its changes directly affect the changes in ecosystems. This study adopts carbon module in invest to evaluate carbon sequestration in the study area. The formula is as follows [47]:

$$C = C_{above} + C_{below} + C_{soil} + C_{dead} \quad (15)$$

where C represents total carbon sequestration in the ecosystem; C_{above} represents above-ground carbon sequestration; C_{below} represents underground carbon storage; C_{soil} represents soil carbon storage; and C_{dead} represents dead organic carbon storage.

(4) Natural landscape recreation

Cultural services refer to the nonmaterial benefits that humans obtain directly or indirectly from the ecosystem, and the leisure and entertainment that humans obtain from natural ecosystems are natural landscape recreation services, which are one of the cultural services. Due to the various types of entertainment in Hebei, this work only takes natural landscape recreation into consideration to simplify the model. The natural landscape that can provide entertainment in Hebei is mainly grassland and forest, such as Aaihanba forest park, Fengning upper dam grassland, and Mulan paddock. NDVI is an important land vegetation ecosystem status parameter and can indicate vegetation coverage [48]. Therefore, this paper selects the annual NDVI composite value of the study area to replace the natural landscape recreation service [49] according to the availability and scientific nature of the data.

3.4. Hotspot Analysis of Ecosystem Services

Hotspot analysis is a technique used to identify the region where the value that is of high interest occurs [50]. In this study, the grids where water production services, soil conservation services, carbon sequestration services, and natural landscape recreation services exceed their respective average values in the study area are used as hotspots for this type of service. After spatial overlay of the hotspots of these four types of ESs, the distribution of the hotspots of multiple ESs in the study area can be obtained. If the values of the four ESs in a grid do not exceed their corresponding average values, the grid unit is defined as a category: 0 service area; if the value of only one ES exceeds the average value, the grid unit is defined as a category: 1 service area; by that analogy, 2 service area, 3 service area and 4 service area can be defined.

3.5. The Assessment of HWB

According to the MA framework, HWB is divided into health, safety, good relationships, basic material needs of maintaining a high-quality life, and the freedom of choice and action. Based on the framework proposed by MA, and combined with the availability of statistical yearbook data, this research selects five indicators to represent HWB in Hebei, which is shown in Table 3. Gross domestic product refers to the final product and labor value of all units in a region within a certain period of time, which can measure the economic conditions and development level of a region. We employed it to characterize basic material needs of maintaining a high-quality life. The number of beds in hospitals and health centers can present local medical level, which can be a suitable indicator to evaluate body health. Body health is an important component of health of HWB. Therefore, number of beds in hospitals and health centers was used to characterize health. Social security was measured by the number of beds in social welfare institutions, which can reflect the resilience of society and social security capability. Effective social security is an indispensable part of safety of HWB. Hence, the number of beds in social welfare institutions was adopted to characterize safety. Good relationships contain social cohesion, mutual respect, and the ability to help others according to MA [6]. However, good relationships are rather subjective and difficult to measure by objective indicators. The study indicated that the higher level of education was beneficial to good social relationships [51]. Under the condition that relative subjective data to measure good relationships was lacking, we selected educational level to reflect indirectly good relationships of HWB. Therefore, the number of students in ordinary secondary schools was selected to represent good relationships. Household deposits in financial institutions at the end of the year can indicate the economic freedom to some extent, which is also the economic foundation of the freedom of choice and action. Hence, household deposits in financial institutions at the end of the year was chosen to characterize the freedom of choice and action.

Table 3. The indicators system of evaluating HWB.

Factor Arrangement	Target Arrangement	Indicator Arrangement
Basic material needs of maintaining a high-quality life	Economic development	Gross domestic product
Health	Body health	Number of beds in hospitals and health centers
Safety	Social security	Number of beds in social welfare institutions
Good relationships	Educational level	Number of students in ordinary secondary schools
The freedom of choice and action	Economic freedom	Household deposits in financial institutions at the end of the year

3.6. The Analysis of Trade-Offs/Synergies

(1) Correlation analysis

In this study, we conduct correlation analysis by MATLAB, and the formula is as follows:

$$\mathrm{r} = \frac{\sum_{n=1}^{n}\left(S1_{n(ij)} - \overline{S1_{(ij)}}\right)\left(S2_{n(ij)} - \overline{S2_{(ij)}}\right)}{\sqrt{\sum_{n=1}^{n}\left(S1_{n(ij)} - \overline{S1_{(ij)}}\right)^2 \sum_{n=1}^{n}\left(S2_{n(ij)} - \overline{S2_{(ij)}}\right)^2}} \tag{16}$$

where S_1 and S_2 represent two variables; r is the correlation coefficient between these two variables; *i* and *j* represent the row and column numbers in the raster data, respectively; and n is the time series of raster data. If the correlation coefficient is positive, it indicates that there is a synergistic relationship between different variables; if the correlation coefficient is negative, it indicates that there is a trade-off relationship between different variables;

if the correlation coefficient is zero, it indicates that there is no relationship between the two variables.

(2) *t*-Test

According to the *t*-test to judge the significance of the relationship between the two variables, the calculation formula of the *t*-test is as follows:

$$t = \frac{\overline{X}_1 - \overline{X}_2}{\sqrt{\frac{(n_1-1)S_1^2+(n_2-1)S_2^2}{n_1+n_2-2}\left(\frac{1}{n_1}+\frac{1}{n_2}\right)}} \tag{17}$$

where S_1 and S_2 are the variances of the two samples, and n_1 and n_2 are the sizes of the two samples. According to the *t* value, the *p*-value can be determined by consulting the corresponding limit value table.

According to the correlation coefficient and *p*-value, the significance levels of the trade-off and synergy can be divided as follows: strong synergy (r > 0, 0.01 < p < 0.05); medium synergy (r > 0, 0.05 < p < 0.1); weak synergy (r > 0, 0.1 < p); weak trade-off (r < 0, 0.01 < p < 0.05); medium trade-off (r < 0, 0.05 < p < 0.1); and strong trade-off (r < 0, 0.1 < p), and others are non-relationship (no correlation relationship).

4. Results

4.1. Land-Use Change

4.1.1. Land-Use Structure Change

The land-use conditions in Hebei during 2000–2015 are shown in Figure 2 and Table 4. Farmland is the main land-use type in Hebei. During the study period, the areas of farmland, grassland, water body, and bare land decreased, while forest and urban land area increased. Among them, the area of farmland has decreased the most, with a decrease of 1155 km^2, and its proportion has decreased from 52.48% to 51.86%; the area of urban land has the most increase, with an increase of 1492 km^2, and its proportion has increased from 7.18% to 7.98%; The proportion of grassland, water body, and bare land area decreased from 17.83%, 2.03%, and 1.05% to 17.71%, 2.01%, and 1.01%, respectively; the forest area remained unchanged.

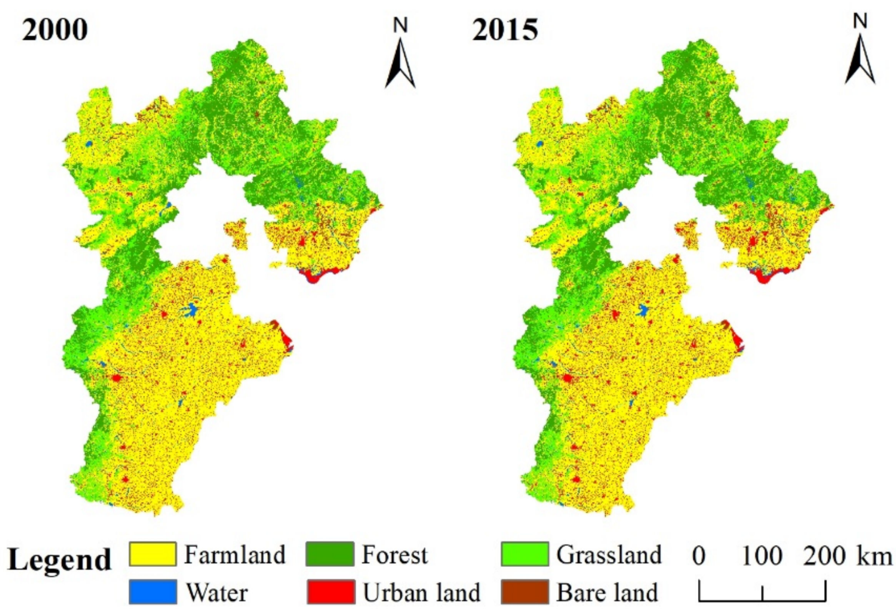

Figure 2. Land-use type of Hebei from 2000–2015.

Table 4. Land-use structure in Hebei of 2000 and 2015.

Time	Item	Farmland	Forest	Grassland	Water Body	Urban Land	Bare Land
2000	Areas/km^2	97,231	35,993	33,040	3766	13,302	1938
	Proportion/%	52.48	19.43	17.83	2.03	7.18	1.05
2015	Areas/km^2	96,076	36,001	32,825	3714	14,793	1861
	Proportion/%	51.86	19.43	17.71	2.01	7.98	1.01

4.1.2. Land Use Transformation

The land-use transfer matrix of Hebei from 2000–2015 is shown in Table 5. During 2000–2015, Hebei had the largest amount of farmland transferred, and its area increase mainly come from water bodies, bare land, and grassland. The amount of land transferred to urban land was second, and the increase in area was mainly from farmland, grassland, and forest. The transferred-in area of farmland, grassland, water body, and bare land was smaller than the transferred-out area, resulting in a decrease in their area. Other land-use types have also undergone varying degrees of conversion.

Table 5. Land-use transfer matrix of Hebei from 2000–2015.

All Types of Land in 2000/km^2	All Types of Land in 2015/km^2					
	Farmland	Forest	Grassland	Water Body	Urban Land	Bare Land
Farmland	95,782	42	5	115	1283	4
Forest	16	35,905	4	5	63	0
Grassland	72	28	32,807	27	105	1
Water body	154	22	2	3536	45	7
Urban land	6	2	3	9	13,282	0
Bare land	46	2	4	21	15	1850

4.1.3. Land-Use Intensity Change

The LUI results of 2000 and 2015 in Hebei is shown are Figure 3. It is known that the LUI in southeastern Hebei is relatively high, where the main land-use cover is farmland and scattered urban land. In contrast, the LUI in northern Hebei is relatively low, where part of grassland and forest are famous tourist areas in Hebei. In general, there was a slight increase in LUI during 2000–2015. According to Figure 3, the sharp increase of LUI is in Tangshan, Qinhuangdao, and Baoding.

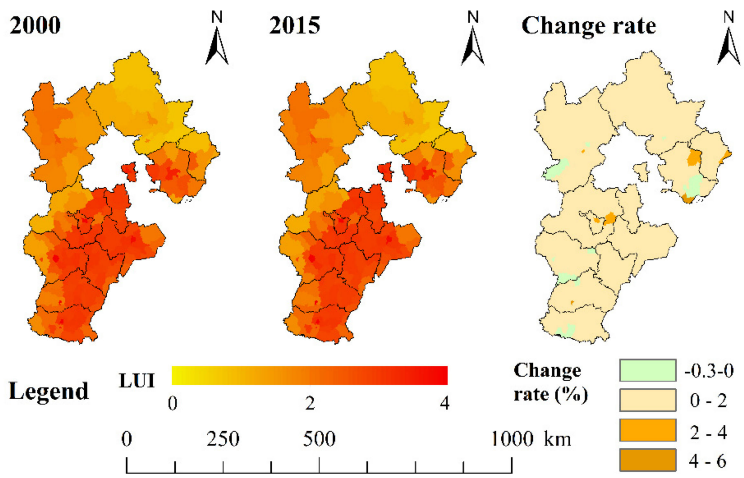

Figure 3. The land-use intensity of 2000 and 2015 and the change rate of LUI during 2000–2015 in Hebei.

4.2. Spatiotemporal Change of Ecosystem Services

The results of ES assessment are shown in Figure 4. From the perspective of the spatiotemporal distribution pattern, the water yield of Hebei over 15 years has changed considerably. Northern Hebei had a lower value of water yield in 2000, while a small part of southern Hebei had a higher value of water yield. In contrast, the distribution of water yield in 2015 showed a trend of gradually decreasing from the Beijing center to the surroundings. The difference in water yield between 2000 and 2015 shows that the main growth areas of water yield are around Beijing and Tianjin. The change in Hebei's water yield was dominated by precipitation based on metadata. From 2000 to 2015, carbon sequestration in Hebei showed an increasing trend in most regions and a decreasing trend in some small region of eastern Hebei. The carbon sequestration in Chengde and Zhangjiakou was basically unchanged. The decline in carbon sequestration was mainly caused by urbanization, which can easily be deduced. In contrast, the increase in carbon sequestration may mainly be dominated by precipitation increasing. The precipitation increasing was beneficial to vegetation growth, which contributes to the increase in carbon sequestration. For soil conservation in Hebei during 2000–2015, most areas in Hebei experienced a little increase in soil conservation, especially in Baoding, Zhangjiakou, and Chengde. In contrast, Xingtai and Handan experienced a decrease during 2000–2015, which was probably due to ecological protection projects for Taihang Mountain. For natural landscape recreation in Hebei during 2000–2015, there was obvious spatial heterogeneity in natural landscape recreation differences. The natural landscape recreation in Chengde obviously increased during the 15 years, which can attribute to ecological protection in Mulan paddock, Fengning upper dam grassland, and Saihanba. The main decrease distributed in Tangshan and Cangzhou, which was due to the quick urbanization and tourism development.

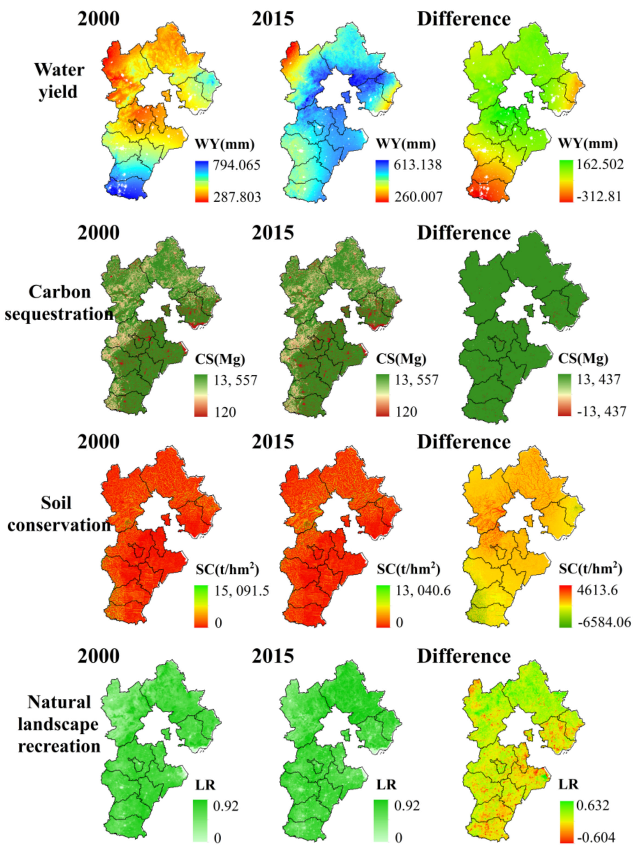

Figure 4. The spatiotemporal distribution and difference of water yield, carbon sequestration, soil conservation, and natural landscape recreation in Hebei during 2000–2015.

4.3. The Spatiotemporal Change of Human Well-Being

The spatiotemporal distribution and difference of HWB in Hebei from 2000–2015 are shown in Figure 5. The basic material needs of maintaining a high-quality life have steadily improved, the high-value district is distributed around Tianjin and Shijiazhuang, and Tangshan and Langfang have increased the most, but some counties have a downward trend. Healthy changes show regional heterogeneity, and the main growth area is in Chengde, Tangshan, and Qinhuangdao. Safety presented a trend of gradually declining north to south in 2000, but the distribution was balanced in 2015. The high-value district of good relationship was mainly distributed on both sides of Tianjin and Handan in 2000, while high-value districts were in Shijiazhuang and Langfang in 2015. The high-value district of the freedom of choice and action has not changed during the past 15 years and is still in Shijiazhuang, Handan, and the neighborhood of Tianjin. In general, the HWB of Hebei during 2000–2015 increased significantly, with high-value districts in Shijiazhuang, Handan, and the neighborhood of Tianjin.

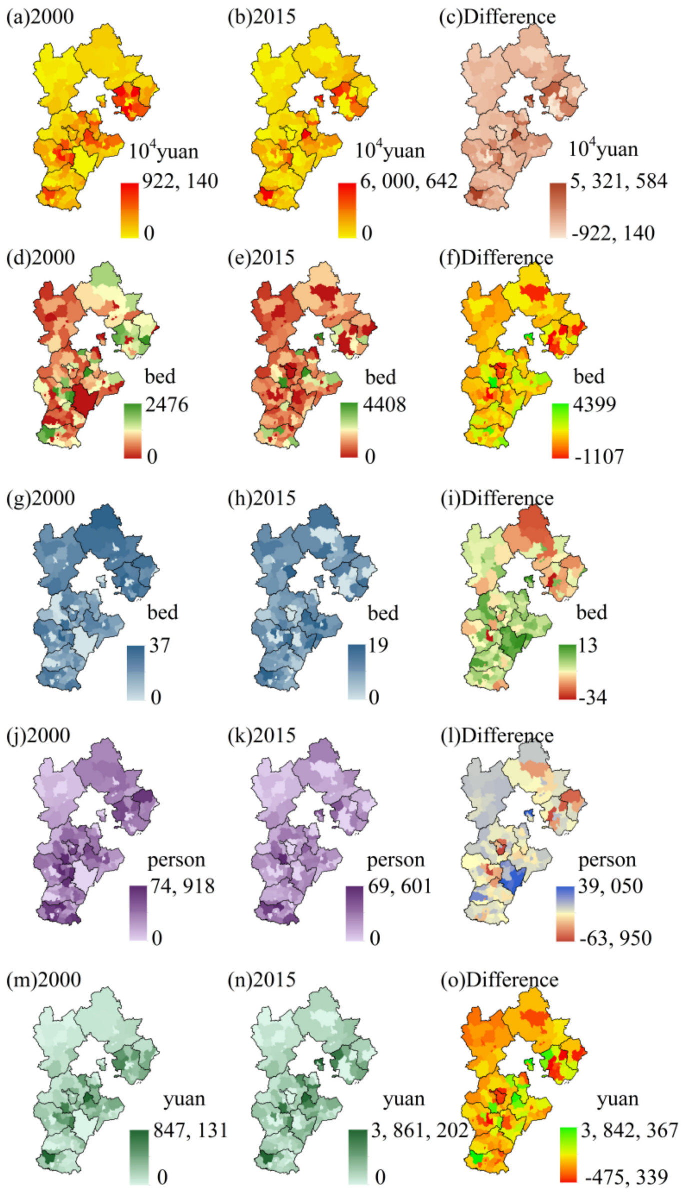

Figure 5. Spatiotemporal distribution of HWB in Hebei from 2000–2015: (**a**–**c**) basic material needs of maintaining a high-quality life; (**d**–**f**) health; (**g**–**i**) safety; (**j**–**l**) good relationship; and (**m**–**o**) the freedom of choice and action.

4.4. Analysis of Trade-Offs/Synergies among Land-Use Intensity, Ecosystem Services, and Human Well-Being

First, in order to keep data consistency, the LUI difference data, four types of ES difference maps, and five types of HWB difference maps from 2000 and 2015 were normalized and resampled into 1 KM, respectively. Then, the four normalized ES difference maps were added to obtain the total ESs of Hebei and five normalized HWB difference maps were also added to obtain the total HWB of Hebei. Finally, the three indicators (LUI difference, total ES difference, and total HWB difference) were subjected to correlation analysis by MATLAB. The following analysis of trade-offs/synergies was also based on the LUI difference, total ES difference, and total HWB difference during 2000 and 2015.

4.4.1. Identification of Hotspots for ESs

The results are shown in Figure 6. It can be known that 0 service area accounts for 8.82% of Hebei in 2000, while it only accounts for 6.5% in 2015. The 1 service area fell from 24.91% to 22.1%, mainly distributed in the northwestern Hebei, in which the altitude is high; the 2 service area increased from 33.59% to 35.38%, and the area of the 2 service area is largest among these five types of service area; the area of the 3 service area increased from 27.49% to 29.98%; the area of the 4 service area increased from 5.19% to 6.04%, but the spatial distribution of the 4 service area changed significantly. The main change is that most areas in Langfang and Cangzhou with 1 and 2 service areas transfer into 3 and 4 service areas. In general, the overall ESs in Hebei were promoted during 2000–2015, and the improvement area was mainly gathered in the surroundings of Beijing and central Hebei.

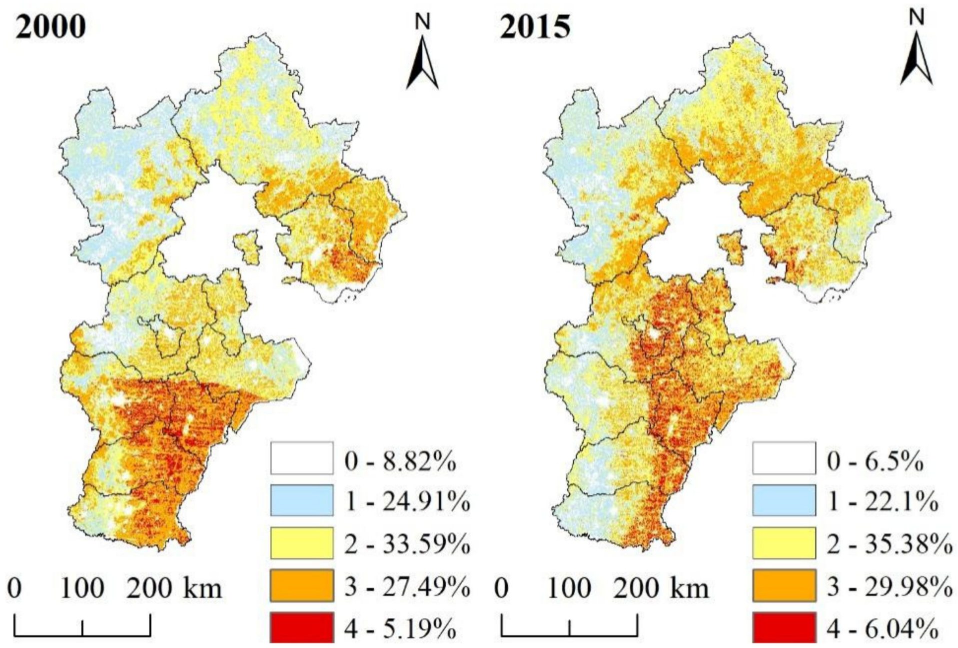

Figure 6. Distribution of the hot spots of multiple ESs in Hebei during 2000–2015.

4.4.2. The Trade-Offs/Synergies between LUI and ESs

We conduct an analysis of trade-offs/synergies between LUI and ESs in Hebei, and the result is shown in Figure 7. We count the area of different relationships, and the results are shown in Table 6. During 2000–2015, most areas in Hebei showed synergy between LUI and ESs, and the synergy area can reach 71.18%, with weak synergy of 37.4%, strong synergy of 18.78%, and medium synergy of 15%. From the spatial distribution, weak synergy areas are mainly distributed in northern Hebei, especially in the neighborhood of Beijing. Synergy increases from the neighborhood of Beijing to the distance from Beijing. The pixels in the neighborhood of Tianjin mainly present strong synergy and medium synergy. From these results, it can be seen that the radiation effects of Beijing and Tianjin on their surroundings have increased the intensity of land use and ESs in the area surrounding Beijing and Tianjin under the BTH Coordinated Development strategy. In contrast, the area of trade-off between LUI and ESs reached 7.92%, which was mainly distributed in southern Hebei. This means that the LUI in this region is increasing, while ESs are decreasing. The main reason is that this region is the Taihang Mountain area, and the recent development of tourism has led to intensive human activities, which has damaged the supply of ESs.

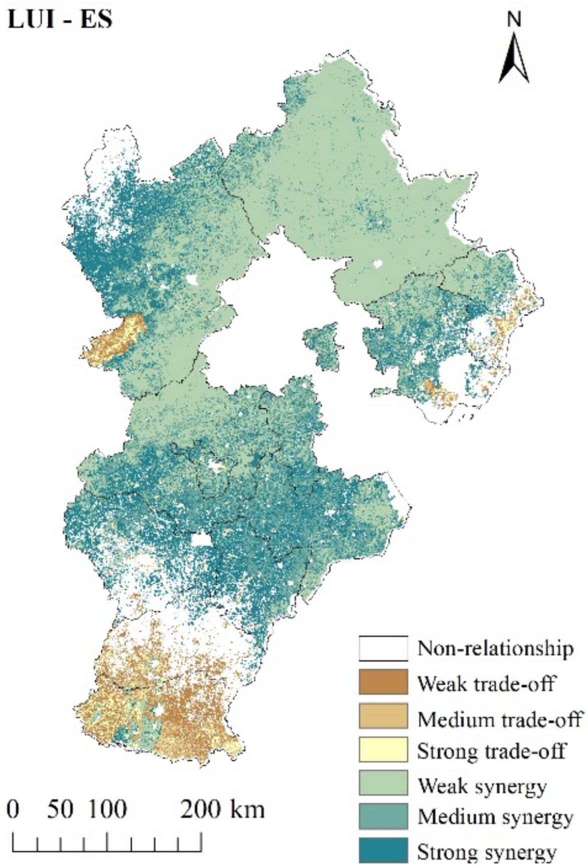

Figure 7. The distribution of trade-offs/synergies between LUI and ESs in Hebei during 2000–2015.

Table 6. The proportion of trade-off/synergy area between LUI and ESs in Hebei during 2000–2015.

LUI-ES	Type	Proportion	
Trade-off	Weak trade-off	4.42%	7.92%
	Medium trade-off	1.83%	
	Strong trade-off	1.67%	
Synergy	Weak synergy	37.40%	71.18%
	Medium synergy	15.00%	
	Strong synergy	18.78%	
Non-relationship	Non-relationship	21%	21%
Total	Total	100%	100%

4.4.3. The Trade-Offs/Synergies between LUI and HWB

The HWB data at county scale were normalized and spatialized in this study, and then, the trade-offs/synergies with LUI were analysed by MATLAB. The result is shown in Figure 8. The area of different relationships is also counted based on Figure 8, and the results are shown in Table 7. Excluding non-relationship areas, the relationship of LUI and HWB mainly presented a trade-off in Hebei during 2000–2015, which reached 32.82%, with a strong trade-off of 17.83%, followed by a weak trade-off of 11.02% and a medium trade-off of 3.97%. From the perspective of spatial distribution, the trade-off areas are mainly distributed in northeastern and central Hebei. The northeastern Hebei mainly represents part of Chengde, Qinhuangdao, and Tangshan. In recent years, tourism development in these areas has increased the intensity of land use, but the overall HWB has not been improved accordingly. Central Hebei is mainly near the provincial capital Shijiazhuang. In contrast, the areas of synergy only reached 19.6% in Hebei during 2000–2015, and they were mainly medium synergy and strong medium. They are distributed in southeastern Hebei, which is the agricultural area of Hebei. It is evident that urban development did not improve HWB in Hebei during 2000–2015. It is worth mentioning that there is an uncertainty in the research because the HWB data are at county scale.

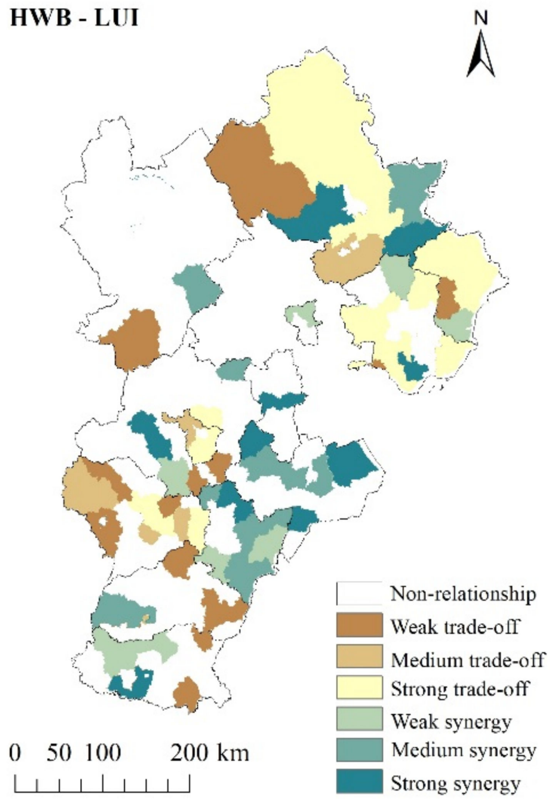

Figure 8. The distribution of trade-offs/synergies between LUI and HWB in Hebei during 2000–2015.

Table 7. The proportion of trade-off/synergy area between LUI and HWB in Hebei during 2000–2015.

HWB-LUI	Type	Proportion	
Trade-off	Weak trade-off Medium trade-off Strong trade-off	11.02% 3.97% 17.83%	32.82%
Synergy	Weak synergy Medium synergy Strong synergy	4.83% 7.42% 7.35%	19.60%
Non-relationship	Non-relationship	48%	48%
Total	Total	100%	100%

4.4.4. The Trade-Offs/Synergies between ESs and HWB

According to the methods mentioned above, we can obtain the spatial distribution of trade-offs/synergies between ESs and HWB in Hebei during 2000–2015, and the result is shown in Figure 9. Then, the proportions of different relationship types were correspondingly counted, which is shown in Table 8. From the results, ES and HWB are the most relevant. Among them, the areas of trade-offs come in 54.48%, especially in the strong trade-off of 35.18%. From the perspective of spatial distribution, strong trade-offs are mainly distributed in Chengde, Tangshan, Qinhuangdao, and parts of Baoding, while weak synergy with 16.96% is dominant in synergy areas, mainly distributed in Cangzhou and Hengshui. Combined with the result of hotspots of ESs, it can be seen that the increase of 4 service areas is consistent with the synergy areas of ES-HWB. Overall, the ESs and HWB in Hebei have been mainly trade-offs in the past 15 years. That is, the improvement of HWB in Hebei in the past 15 years has been accompanied by a decline in the supply of ES.

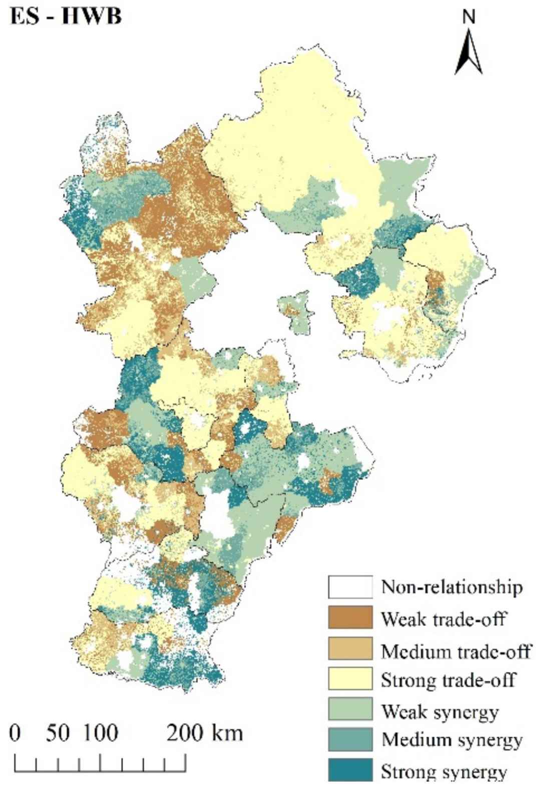

Figure 9. The distribution of trade-offs/synergies between ESs and HWB in Hebei during 2000–2015.

Table 8. The proportion of trade-off/synergy area between ESs and HWB in Hebei during 2000–2015.

ES-HWB	Type	Proportion	
Trade-off	Weak trade-off Medium trade-off Strong trade-off	11.59% 7.71% 35.18%	54.48%
Synergy	Weak synergy Medium synergy Strong synergy	16.96% 5.59% 7.82%	30.37%
Non-relationship	Non-relationship	15.15%	15.15%
Total	Total	100%	100%

4.4.5. The Analysis of Trade-Off/Synergies among LUI, ESs, and HWB

Because previous studies do not have the methods to analyze and express trade-offs/synergies of three variables simultaneously, this study proposes a framework to express trade-off/synergies of LUI, ES, and HWB in one map based on spatial analysis and logical analysis in ArcGIS. The trade-offs/synergies of LUI-ES, LUI-HWB, and ES-

HWB were used to obtain the trade-offs/synergies of LUI-ES-HWB, and the results are shown in Figure 10. We divide these relationships into four types: 1 represents trade-off of LUI-ES and trade-off of LUI-HWB, while ES-HWB is synergy; 2 represents trade-off of ES-LUI and trade-off of ES-HWB, while LUI-HWB is synergy; 3 represents trade-off of HWB-LUI and trade-off of HWB-ES, while LUI-ES is synergy; and 4 represents synergy among LUI-ES-HWB.

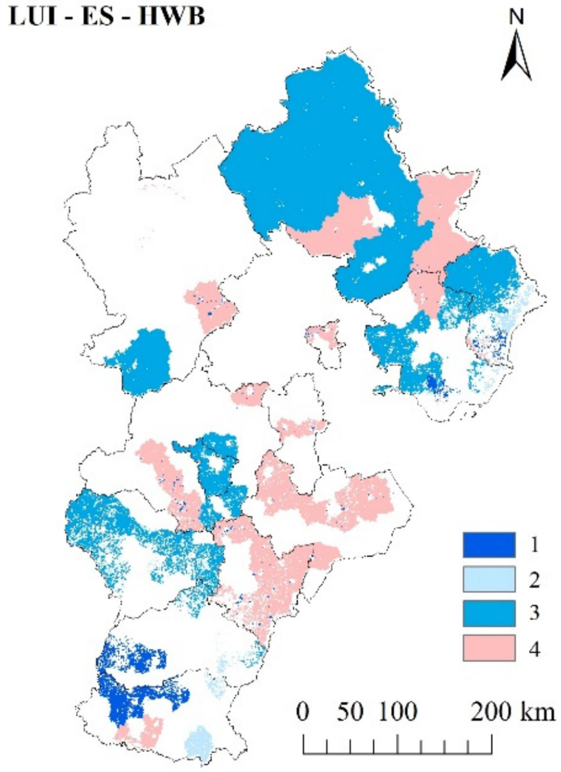

Figure 10. The distribution of trade-offs/synergies among LUI, ESs, and HWB in Hebei during 2000–2015. Note: 1 represents the trade-off between LUI—(ES and HWB), while ES-HWB is synergistic; represents the trade-off between ES—(LUI and HWB), while LUI-HWB is synergistic; represents trade-off between HWB—(LUI and ES), while LUI-ES is synergistic; 4 represents synergy among LUI-ES-HWB.

For the region 1, its distribution is relatively small and only in a small part of Xingtai, Handan, and Qinhuangdao. The main problem for sustainable development is the unreasonable intensity of land use, leading to a competitive relationship with both ES and HWB. Therefore, region 1 needs to adjust the land-use structure to achieve sustainable development. For region 2, the region 2 takes the most area among these four of types regions. Region 2 is mainly distributed in the most areas of Chengde and Shijiazhuang and a small part of Qinhuangdao, Zhangjiakou, and Tangshan. The main problem of region 2 for sustainable development is the uncoordinated development of ESs with land-use intensity and HWB. Therefore, protecting the environment to improve the supply of ESs is urgent in region 2 in order to achieve sustainable development. For region 3, its main distribution is in a small part of Xingtai, Handan, and the coastal area of Qinhuangdao. The main problem limiting sustainable development is that the overall HWB cannot increase with LUI and ESs. Hence, to solve the regional problem in region 3, we should devote ourselves to the improvement of comprehensive regional HWB from different perspectives. Region 4 is the area of synergy among LUI, ESs, and HWB, and it is mainly distributed in central and northeastern Hebei. Compared with the hotspots of ESs, central Hebei is the area with the most obvious growth in the 4 service areas, and it coincides with the region

4. This shows that the integrity of the ES supply provides important support for regional sustainable development.

5. Discussion

5.1. Interpretation of the Results

(1) The analyses of changes in the hotspots of ESs. In general, the overall ecological environment has improved, and the assessment results are consistent with previous studies by other methods [52,53]. According to the results of the study, the great changes of hotspots of ESs in Hebei during 2000–2015 can be concluded into two aspects: one is the obvious increase of hotspots of ESs in the surroundings of Beijing and Tianjin, especially in Langfang, Baoding, and Changzhou; another is the decrease of hotspots of ESs in the piedmont plain of the Taihang Mountains, especially in Shijiazhuang, Xingtai, and Handan. For the hotspot changes in the surroundings of Beijing and Tianjin, this can be attributed to the context of BTH Coordinated Development, and the surroundings of Hebei and Tianjin benefit from a series of environmental protection policies in Beijing and Tianjin so that their ES hotspots increase [54]. For the hotspot changes in the piedmont plain of the Taihang Mountains, the decrease of hotspots is mainly related to changes in water yield service and carbon sequestration service, which can be attributed to changes in precipitation and evapotranspiration in Hebei [55].

(2) The results of trade-offs/synergies in Hebei during 2000–2015. Most areas of Hebei show synergistic relationship between LUI and ES, which indicates that Hebei's urban development and economic construction have not exceeded the ecological boundaries. However, the trade-off region of LUI and ES in southern Hebei shows that economic development and environmental protection conflicts in Hebei still exist. This outcome is consistent with Zhang et al. [56]. In the analysis of trade-offs/synergies between LUI and HWB, the proportion of trade-off area is higher than that of synergy area. This shows that the development of urbanization does not promote local HWB in some areas of Hebei; this phenomenon has also appeared in previous studies [49]. In addition, more than half of the regions of Hebei present trade-offs between ES and HWB. In summary, Hebei is committed to economic development and environmental protection, but it has not taken HWB into careful consideration, leading to HWB having a competitive relationship with LUI and ES in many regions of Hebei.

(3) Regional solutions for sustainable development: This study pointed out the main regional problem according to the analysis of trade-offs/synergies among LUI, ES, and HWB in Hebei. The synergistic areas of LUI, ES, and HWB are mainly distributed in the southeastern part of Hebei. This area is the ecological restoration area of the piedmont plain of Taihang mountain, the ecological barrier in the southern of Beijing, and the farmland ecological reserve of Hebei. This area can provide experience in cooperating the development of the LUI-ES-HWB for other regions of Hebei. For the regions of uncooperating development of LUI-ES-HWB, we proposed related solutions based on their main problems. It is remarkable that the Chinese government divided 168 countries of Hebei into five partitions according to different ecological patterns in 2015 [57]. They are the ecological protection area of dam plateau, ecological conservation area of Yanshan-Taihang mountain, ecological repair area of low plain, coastal marine ecological protection area, and Beijing-Tianjin-Baoding center ecological transitional belt. Different partitions have different core tasks to jointly build the ecological security pattern of Hebei Province and provide important ecological support for Beijing-Tianjin-Hebei sustainable development [58].

5.2. Limitations of Methods

Previous studies usually map and analyze the trade-offs/synergies of ecosystem services [59] or the trade-offs/synergies between ecosystem services and other variances. However, it is difficult to analyze and express the trade-offs/synergies of two or more types of variances by existing methods. This paper proposes a framework to explore the trade-offs/synergies among LUI, ES, and HWB and analyzes their spatiotemporal characteristics to contribute to regional coordinated development. However, there are still limitations in the research methods. First, we adopted 2000 and 2015 to conduct the study. The two-year data can reflect the change in the time cut-off point, but they cannot capture the fluctuation information within the time range [60]. Long time-series data are needed in future studies to explore the intensity of land use, the process of ESs, and the response to HWB. Second, this paper explored the trade-offs/synergies of LUI, ES, and HWB and identified regions of different relationships, which provides scientific solutions for regional sustainable development. However, ongoing research still needs to strengthen the understanding of the mechanism of trade-offs and synergy [61], especially the response of HWB to changes in LUI and ES. At the same time, distinguishing the contribution of land-use change and climate change to changes in HWB is also difficult at this stage. Finally, this study adopts objective HWB data at the county scale due to the availability of data. However, HWB contains subjective and objective HWB and, focusing only on objective well-being, cannot lead to a comprehensive assessment of regional HWB [62]. Therefore, the method of combining subjective well-being and objective well-being should be used in future studies. Furthermore, HWB at the county scale participated in the comprehensive study of land use and ESs cannot reflect the heterogeneity of HWB and ignores the relationship among LUI, ES, and HWB within the county. Finer resolution of HWB data is needed in the future studies.

5.3. Recommendations

In general, in most areas of Hebei during 2000–2015, the land-use intensity was increased, the supply of ESs improved, and HWB was promoted. However, LUI, ES, and HWB do not develop synergistically in most areas. Due to the poor ecological environment in Hebei, the ecosystem of Hebei is still under great pressure facing economic transformation and accelerated urbanization [53]. To positively respond to major national strategies for BTH Coordinated Development and meet increasing people's demand for ecological and environmental services, we put forward corresponding recommendations for regional sustainable development:

(1) The land-use structure should be adjusted in coastal regions of northern Hebei;
(2) The government should concentrate on improving the overall HWB in northern Hebei and the surroundings of Shijiazhuang, the capital of Hebei Province;
(3) The local government should commit to protecting the environment to improve the ability of ES supply, especially the integrity of ESs.

6. Conclusions

Understanding the trade-offs/synergies among LUI, ESs, and HWB can promote the balance among economic development, ecological protection, and the improvement of HWB. However, due to the lack of methods to analyze and express the trade-offs/synergies of two or more types of variances, simultaneously conducting quantitative analyses of trade-offs/synergies among LUI, ESs, and HWB remains challenging. The purpose of this work is to propose a framework that can simultaneously analyze and express the trade-offs/synergies among LUI, ESs, and HWB and provide solutions to achieve the efficient management of the ecosystem and improve HWB. This work employed related models to assess LUI, ESs, and HWB in Hebei during 2000–2015 based on remote sensing data, soil data, meteorological data, and socioeconomic data. Then, we mapped and analyzed the trade-offs/synergies among LUI, ESs, and HWB through correlation analysis and spatial analysis. Finally, we pointed out the main problems of different regions with sustainable development according to the results. This study not only provided a framework to explore the trade-offs/synergies among three types of variances but also proposed related regional solutions for managing Hebei ecosystem into a sustainable manner. The results of this study are shown as follows during 2000–2015 in Hebei:

(1). Although there is a large transformation in land-use types, a series of ecological protection policies have maintained the balance of land-use structure;

(2). The overall ESs of Hebei were improved, and the areas of improvement were mainly concentrated in the surrounding areas of Beijing and the piedmont plain of Taihang Mountain;
(3). LUI and ES mainly presented a synergistic relationship, while HWB and LUI mainly presented a trade-off relationship, and ES and HWB also present a trade-off relationship;
(4). To achieve sustainable development, region 1 needs to adjust land-use structure, region 2 needs to protect the ecological environment to improve the supply of ESs, and region 3 needs to commit to improving the comprehensive regional HWB.

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